Status and Phenomenology of the Standard Model

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The status of the new standard model is briefly surveyed, with emphasis on experimental tests, unique features, theoretical problems, necessary extensions, and possible TeV signatures of Planck scale physics.

1 The *New* Standard Model

The New Standard Model (NSM)[1]) is the original SM $(SU(3){\times}SU(2){\times}U(1)\times$ classical general relativity), supplemented with neutrino mass, which can be Dirac or Majorana. The focus of this talk will be on the electroweak $(SU(2){\times}U(1))$ sector.

The NSM is a mathematically consistent field theory of the strong, weak, and electromagnetic interactions and classical gravity that is the correct description of nature to first approximation down to $\sim 10^{-16}$ cm. However, it is a complicated theory with many free parameters and fine tunings, strongly suggesting that there must be new physics beyond the standard model (BSM) at shorter distance scales, and in fact most particle physicists are involved in one way or another in the search for that new physics.

The standard model has many special features that are *usually not* maintained in BSM, leading both to a challenge for theorists in constructing new models and an opportunity for experimentalists searching for hints of new physics. These include:

− The neutrino masses m_ν were predicted to vanish in the *old* standard model. One would need to add singlet fermions and/or triplet Higgs fields and/or higher dimensional operators (HDO) for nonzero masses. However, almost all extensions of the SM predicted one or more of these.

− Yukawa couplings are proportional to fermion masses, $h_f \propto gm_f/M_W$, implying that the Higgs couplings are small for the light fermions and that they are flavor conserving. This is partially maintained in the Minimal Supersymmetric Standard Model (MSSM) and simple two Higgs doublet models but usually not in more complicated Higgs models.

− There are no flavor changing neutral currents (FCNC) mediated by the Z, γ, or Higgs (H) at tree level. Lepton flavor is conserved to all orders for massless neutrinos (and the *direct* effects of $m_\nu \neq 0$ for charged lepton processes are negligible). Quark FCNC at loop level are suppressed (the GIM mechanism). There are enhanced FCNC effects in most extensions of the SM, including new loop effects in supersymmetry, new interactions in dynamical symmetry breaking, Little

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[1]) For a general review, see [1].

Higgs models, possible heavy Z' bosons with non-universal couplings (motivated in some string constructions), and multiple Higgs doublets.

– Off-diagonal CP violation (e.g., in K and B mixing and decays) is suppressed, while diagonal CP violation, i.e., electric dipole moments (EDM), is highly suppressed. Extensions again typically offer new sources of enhanced CP violation, such as possible new $\not{C}P$ phases in supersymmetry (μ and soft parameters, and the associated supersymmetric loops), and phases associated with additional Higgs and exotic fields or new non-universal Z' bosons.

– Baryon (B) and lepton (L) number are conserved perturbatively (and $B - L$ non-perturbatively) in the SM, while they can be violated in BSM, such as grand unified theory (GUT) or string interactions, possible R-parity violation ($\not{R}_p$) in supersymmetry, and Majorana neutrino masses.

2   Experimental Precision Tests

Let me briefly comment on some of the experimental tests of the standard electroweak model.

2.1   The Weak Charged Current

Like QED, the Fermi Theory of the weak charged current interactions had been developed and tested prior to the standard model. However, it was successfully incorporated and greatly improved by being made renormalizable, which allowed the calculation of radiative corrections. Much of the recent activity has involved study of the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$V = \left(\begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{td} & V_{td} \end{array} \right),$$

which measures the mismatch between the family structure of the left-handed u-type and d-type quarks. For 3 families V involves three angles and one CP-violating phase after removing unobservable q_L phases. The corresponding right-handed quark mixings are unobservable in the SM, but could be if there were new interactions involving q_R. There have been extensive recent studies, especially in B and K decays [2, 3, 4], to test the unitarity and consistency of V as a probe of new physics and to test the origin of CP violation[2]). The longstanding hint of a 2.4σ discrepancy in the universality prediction $|V_{ud}^2| + |V_{us}^2| + |V_{ub}^2| = 1$ has recently been resolved by new measurements of $|V_{us}|$ by the BNL-E865, Fermilab KTeV, CERN NA48, and $DA\Phi NE$ KLOE experiments [4], which yield a higher value than the previous world average.

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[2]) An additional source of CP breaking is required for baryogenesis.
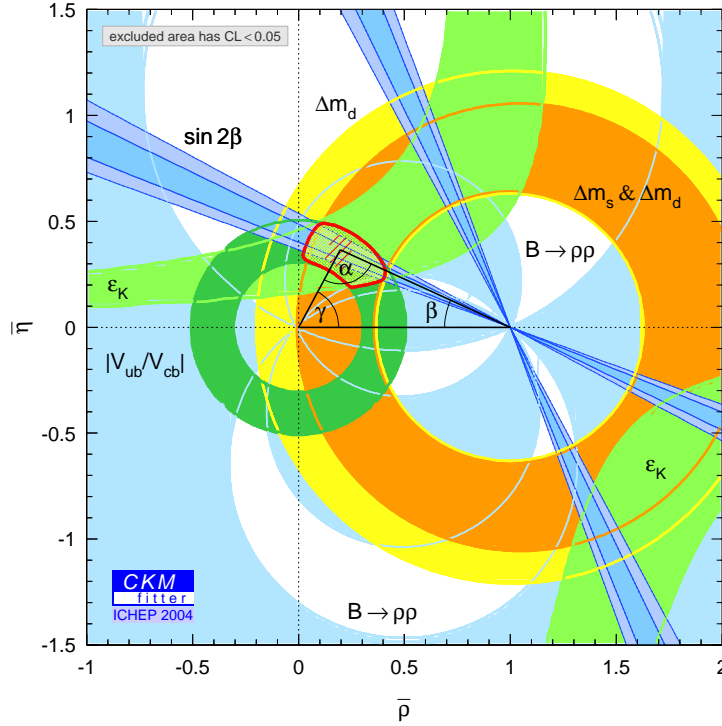
Fig. 1. The current status of the unitarity triangle, from [5].

The sides of the unitarity triangle are well determined [5] by B decay rates, branching ratios, and oscillations (an actual measurement of B_s oscillations in eagerly awaited), and by CP violation in K decays. The focus has turned to a measurement of the angles from CP violation in B decays in order to overconstrain the system. The Babar and Belle collaborations [2, 3] have obtained the very precise value $\sin 2\beta = 0.726 \pm 0.077$ from $B_d^0(t) \to J/\psi K_{S,L}$, with little theory error. The angles α and γ are more difficult. Recently, direct CP violation in charmless B decays has been established, and precise values for α (e.g., an average $106^{\circ+8^\circ}_{-11^\circ}$ [2]) are emerging. Babar and Belle are now in good agreement on their measurements of $b \to s$ electroweak penguin decays, such as $B^0 \to \phi K^0$. There is some evidence (at about the 2.5σ level) for a discrepancy with the SM expectation. If this were confirmed by future higher precision measurements, it would suggest such new physics as supersymmetric loops (for high $\tan\beta$) [6] or a heavy Z' gauge boson with flavor changing couplings [7]. The latter would be a tree level effect competing with a small SM loop diagram.

Summary 2004

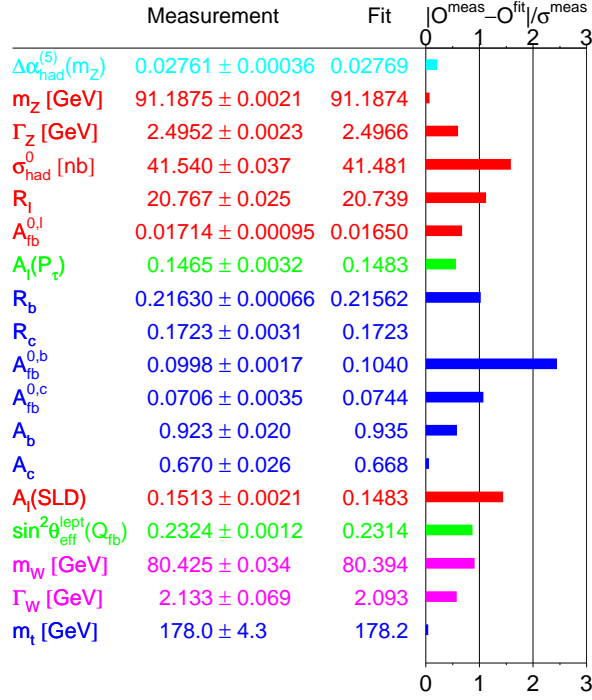|	Measurement	Fit	$|O^{meas}-O^{fit}|/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966	
σ_{had}^0 [nb]	41.540 ± 0.037	41.481	
R_l	20.767 ± 0.025	20.739	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483	
R_b	0.21630 ± 0.00066	0.21562	
R_c	0.1723 ± 0.0031	0.1723	
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040	
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.026	0.668	
$A_l(SLD)$	0.1513 ± 0.0021	0.1483	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.425 ± 0.034	80.394	
Γ_W [GeV]	2.133 ± 0.069	2.093	
m_t [GeV]	178.0 ± 4.3	178.2	

Fig. 2. Precision observables, compared with their expectations from the best SM fit, from [13].

2.2 The Weak Neutral Current

The weak neutral current (WNC), along with the W and Z, have been the primary predictions and tests of the electroweak $SU(2)\times U(1)$ model. The WNC was discovered in 1973 by the Gargamelle collaboration at CERN and by HPW at Fermilab. The structure of the WNC has been tested in many processes [8], including (purely weak) neutrino scattering $\nu e \to \nu e$, $\nu N \to \nu N$, $\nu N \to \nu X$; weak-electromagnetic interference in $e^{\uparrow\downarrow}D \to eX$, atomic parity violation, and recently in polarized Möller scattering [9]; and in e^+e^- scattering above and below the Z pole.

There is generally excellent agreement of the WNC data with the SM pre-

dictions. An apparent discrepancy in the precise Boulder measurement of parity violation in the cesium atom was resolved by improved calculations, especially of the radiative corrections [10]. There is still an $\sim 3\sigma$ discrepancy between the NuTeV ratio of neutral to charged current deep inelastic νN cross sections and the SM expectation [11]. This could possibly be due to new TeV scale effects such as a heavy Z', but may well be a subtle strong interaction effect, such as an $s - \bar{s}$ asymmetry or large isospin breaking in the nucleon sea, or higher order QCD effects [12].

2.3 The LEP/SLC Era

The Z factories LEP and SLC allowed tests of the standard model at a precision of $\sim 10^{-3}$, much greater than had previously been possible at high energies. In particular, the four LEP experiments ALEPH, DELPHI, L3, and OPAL at CERN accumulated some $2 \times 10^7 Z's$ at the Z-pole in the reactions $e^+e^- \to Z \to \ell^+\ell^-$ and $q\bar{q}$. The SLD experiment at SLAC had a smaller number of events, $\sim 5 \times 10^5$, but had the significant advantage of the highly polarized ($\sim 75\%$) SLC e^- beam. The Z pole observables included the lineshape variables, M_Z, Γ_Z, and σ; and the branching ratios into $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ as well as into $q\bar{q}, c\bar{c}, b\bar{b}$, and (less precisely) $s\bar{s}$. These could be combined to obtain the stringent constraint $N_\nu = 2.9841 \pm 0.0083$ on the number of ordinary neutrinos with $m_\nu < M_Z/2$ (i.e., on the number of families with a light ν). This also constrains other invisible Z decays, such as into a light scalar ν in supersymmetry. The Z-pole experiments also measured a number of asymmetries, including forward-backward (FB), polarization, the τ polarization, and mixed FB-polarization, which were especially useful in determining the weak angle $\sin^2 \theta_W$. The leptonic branching ratios and asymmetries confirmed the lepton family universality predicted by the SM. The results of many of these observations, as well as some WNC and high energy collider data, are shown in Figure 2. There is generally excellent agreement with the SM expectations, though there is a hint of a tension between the lepton and quark asymmetries (most apparent in the b quark forward-backward asymmetry $A_{fb}^{0,b}$ and the polarization asymmetry A_l.). This may well be a fluctuation, but could possibly be suggesting new physics affecting the third family.

The LEP II program above the Z-pole provided a precise determination of M_W (as did the Tevatron experiments CDF and D0), measured the four-fermion cross sections $e^+e^- \to f\bar{f}$, searched for the Higgs and for BSM effects such as superpartners, and tested the (gauge invariance) predictions of the SM for the three and four point gauge self-interactions. These had already been indirectly verified by the α_s running in QCD and by the electroweak radiative corrections, but could be probed more directly in $e^+e^- \to W^+W^-$. The SM predicts strong cancellations between the three tree-level diagrams in Figure 3 in the high energy amplitude, which would be upset by anomalous couplings. As seen in Figure 4 the LEP II results are in excellent agreement with the SM prediction.
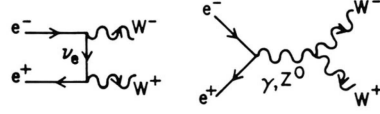
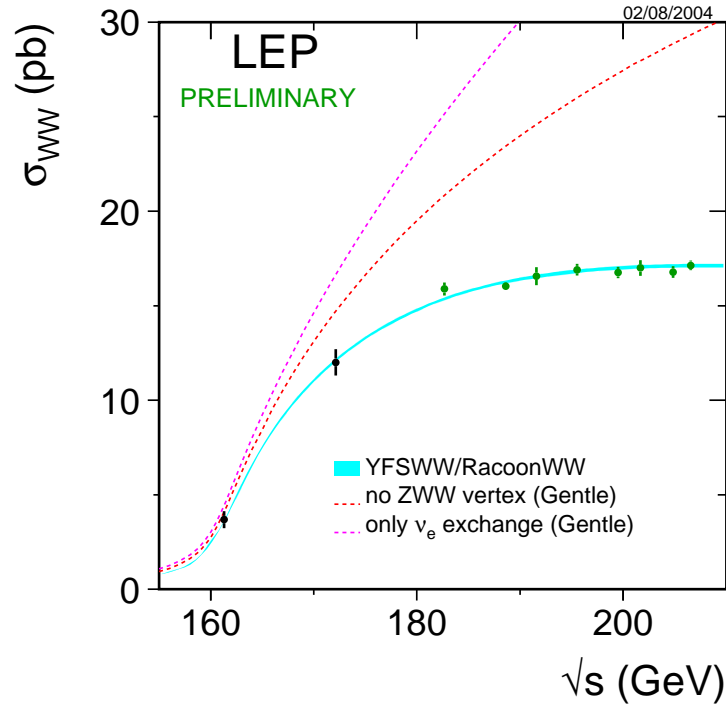Fig. 3. Tree-level diagrams contributing to $e^+e^-{\rightarrow}W^+W^-$

Fig. 4. The $e^+e^-{\rightarrow}W^+W^-$ cross section, compared with the SM expectation, from [13].

2.4 The Anomalous Magnetic Moment of the Muon

The BNL E821 experiment has made an extremely precise measurement of the muon anomalous magnetic moment [14], $a_\mu(\mathrm{exp}) = (11659208.0 \pm 5.8) \times 10^{-10}$, which is 2.4σ above the SM prediction [15] assuming the value for the hadronic vacuum polarization obtained from $e^+e^- \to$ hadrons: one finds $23.9(7.2)(3.5)(6) \times 10^{-10}$ for $\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM})$. The discrepancy is smaller ($\sim 0.9\sigma$) using the value calculated from τ decays. If the discrepancy is real, it could be accounted for in the MSSM by loops involving a scalar muon and a neutralino, or a scalar neutrino and a chargino. One has [15] $\Delta a_\mu(\mathrm{SUSY}) \sim 13 \times 10^{-10} \frac{\tan\beta \ \mathrm{sign}(\mu)}{(M_{\mathrm{SUSY}}/100 \ \mathrm{GeV})^2}$, for common superpartner masses M_{SUSY}, favoring positive μ (the supersymmetric Higgsino mass), large $\tan\beta$ and/or small M_{SUSY}.

2.5 The Precision Program

Altogether, the precision program, including the WNC, the Z and W, the Z-pole and above, and the Tevatron measurements of m_t, have shown that

– The SM is correct and unique to zeroth approximation, justifying the gauge principle as well as the SM gauge group and fermion representations.

– The SM is correct at the loop level, confirming the framework of renormalizable gauge field theory, leading to successful predictions for m_t and α_s, and to a still untested prediction for the Higgs mass M_H. The indirect (precision) data leads to the prediction $M_H = 113^{+56}_{-40}$ GeV, consistent with the direct lower limit $M_H > 114.4$ GeV from the nonobservation of $e^+e^- \to ZH$ at LEP II[3]), while the indirect and direct data together imply $M_H < 246$ GeV at 95% cl [8, 13]. This is consistent with, but does not prove, the MSSM prediction of a light Higgs, e.g., $M_H \lesssim 130$ GeV [6].

– Possible new TeV-scale physics is severely constrained. In particular BSM physics which decouples, such as supersymmetry and unification, is strongly favored over non-decoupling physics, such as most forms of compositeness.

– The precisely measured gauge couplings are consistent with the gauge unification [17] predicted by the MSSM. If this is not an accident or due to a compensation, it strongly limits the possibilities for new TeV scale physics.

3 Problems With the New Standard Model

Despite its successes, the new standard model has a great deal of arbitrariness and fine-tuning [18], as is illustrated by the fact that it has 27 free parameters (29 for Majorana neutrinos), *not* including electric charges. These can be taken to be 3 gauge couplings; the Z and Higgs masses; the QCD θ parameter; 12 fermion masses;

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[3]) The central value is pulled up by $A^{0,b}_{fb}$ and down by A_l. It has increased somewhat due to the new D0 Run I m_t value [16] and a lower M_W.

6 mixings and 2 CP phases (2 additional for Majorana ν's); and the cosmological constant. The Planck scale (Newton constant) is not included because only the ratios of mass parameters are observable. In particular,

– The SM gauge group is complicated: it involves 3 distinct gauge couplings, only the electroweak part is parity-violating, and charge quantization (e.g., $|q_e| = |q_p|$) is put in by hand (anomaly cancellation by itself is not sufficient to determine all of the hypercharge assignments). This suggests some form of unification, such as grand unification (GUT) or string theory.

– The existence of fermion families, the hierarchies of their masses, and the pattern of their mixings are unexplained in the NSM. It is still unknown whether the neutrinos are Dirac or Majorana, and their large mixings and small mass scale compared to other fermions are not understood. The fermion spectrum may well be probing the Planck or GUT scale. In string theories the hierarchies may be associated with higher dimensional operators in heterotic models or with volume-suppressed instanton effects in intersecting brane constructions. Other possibilities include compositeness, family symmetries, radiative hierarchies, or large extra dimensions. Also, the CP violation in the NSM is inadequate to explain the observed baryon asymmetry, suggesting new sources of CP violation, such as new CP phases associated with soft breaking or μ parameters in supersymmetric models of electroweak baryogenesis, or new neutrino phases in leptogenesis.

– Consistency of the SM requires a Higgs mass-squared comparable to the electroweak scale, $M_H^2 = O(M_Z^2)$. However, quadratically divergent higher order corrections, such as shown in Figure 5, yield much larger corrections, $\delta M_H^2/M_Z^2 \sim 10^{34}$, where I have assumed the integrals are cut off at the Planck scale, requiring an extremely fine-tuned cancellation with the tree-level mass-squared. The
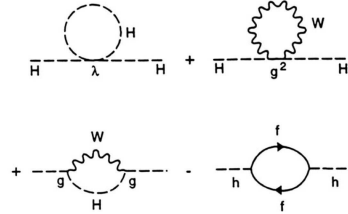

Fig. 5. Quadratically divergent corrections to M_H^2.

traditional solutions to this fine-tuning problem include TeV-scale supersymmetry [6], in which fermion and boson loops cancel; Little Higgs models [19], in which fermions and bosons cancel separately; dynamical supersymmetry breaking (DSB) [20], in which there are no elementary Higgs fields; and large extra dimensions [21], in which the fundamental scale is much lower. Recently, consideration

has been given to theories, such as split supersymmetry [22], in which supersymmetry is broken at a high scale and the Higgs hierarchy problem is apparently solved by a fine tuning, perhaps related to an enormously large "landscape" of superstring vacua [23] and possible anthropic [24] selection principles.

– The strong CP problem [25] refers to the fact that one can add the P, T, and CP-violating term $\frac{\theta}{32\pi^2} g_s^2 F \tilde{F}$ to the QCD Lagrangian, where $\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}/2$ is the dual field and θ is an arbitrary dimensionless parameter. The experimental bound on the neutron electric dipole moment implies $\theta < 10^{-9}$. One cannot simply set θ to zero because weak interaction corrections shift θ by $\delta\theta|_{\text{weak}} \sim 10^{-3}$, again requiring a fine-tuned cancellation between the tree and weak contributions, for which (as far as I am aware) there is no anthropic explanation. Possible solutions include the extension of the SM to include a spontaneously broken global $U(1)$ (Peccei-Quinn) symmetry. This implies the existence of an axion, for which there is still a narrow window for the breaking scale allowed by cosmological and astrophysical considerations [26] (which is small compared to the scale expected in simple string implementations [27]). Other possibilities include an unbroken global $U(1)$, leading to a (disfavored) massless u quark; or spontaneously broken CP (leading to possible cosmological domain wall problems) combined with other symmetries so that θ becomes calculable and small.

– Gravity is not unified with the other interactions. Furthermore, although classical general relativity is included in the SM, it is not renormalizable when quantized. Finally, the vacuum energy $\langle V \rangle$ from electroweak symmetry breaking leads to an effective cosmological constant: $\Lambda_{\text{SSB}} = 8\pi G_N \langle V \rangle$ some 10^{50} times larger than the observed value from the acceleration of the universe, requiring an extremely finely-tuned cancellation with the primodial value. The tuning is even worse ($\Lambda_{\text{SSB}} > 10^{124} \Lambda_{\text{obs}}$) in simple GUT and string constructions. This difficulty is made even worse in that it is not enough to somehow eliminate the string scale contribution - one must simultaneously eliminate the electroweak and the smaller QCD contributions, as well as loop effects. The unification problem is solved in supergravity and Kaluza Klein theories. The extension to superstrings renders quantum gravity renormalizable (in fact finite). There is no known solution to the cosmological constant problem other than an anthropically motivated finetuning associated with the string landscape [23].

3.1 Necessary New Ingredients

New observations as well as the SM problems imply the need for a number of new ingredients. These include

– A mechanism for small neutrino masses [28]. More generally, one is interested in whether the neutrino masses are Dirac or Majorana, whether the spectrum is ordinary or inverted, what the absolute scale is (with implications for cosmology), why two mixing angles are large, the value of the small angle U_{e3} and the CP violating phase, whether the LSND results (which suggest the existence of additional, sterile, neutrinos which mix with the ordinary neutrinos) are confirmed by

MiniBooNE, and whether there are any new ν interactions or anomalous properties. Mechanisms for neutrino mass include some form of seesaw mechanism[4]), perhaps associated with the Planck or GUT scale; heavy Higgs triplets; or small Dirac masses, e.g., from higher-dimensional operators or volume suppressions in theories with LED.
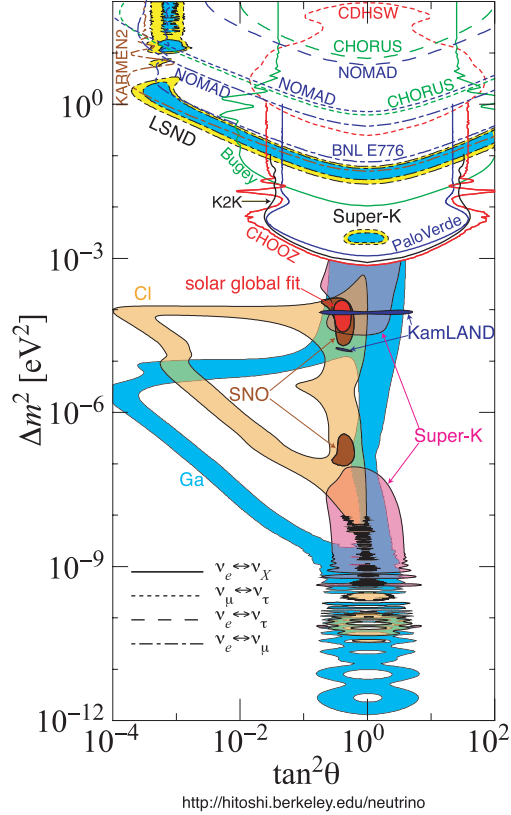

Fig. 6. Current neutrino oscillation results, from [31].

– A mechanism for generating the baryon asymmetry [32], such as electroweak baryogenesis, probably (except for a small parameter range [33]) requiring an enhancement with respect to the MSSM from an extended Higgs sector [34] and/or a Z' [35]; heavy Majorana neutrino decays (leptogenesis), associated with canonical seesaw models; the decay of a coherent field; or CPT violation.

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[4]) The canonical seesaw may not be favored in some superstring constructions [29] or models with a TeV scale Z' [30].

– A mechanism for the dark energy [36], which constitutes about 70% of the energy density of the Universe. Is it a cosmological constant (and if so, why is it so small), or some form of time-varying field (quintessence)? This raises other questions, such as whether it is related to inflation, and whether there is a connection to the (controversial) suggestion of time variation of couplings [37]?

– An explanation for the nature of the dark matter [26] (30%), such as the lightest supersymmetric particle (if R-parity is conserved) or an axion.
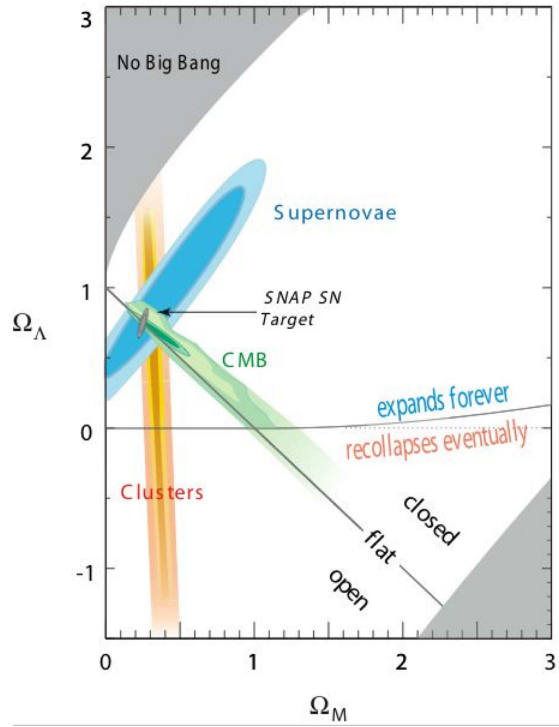

Fig. 7. Current constraints on the dark energy (Ω_Λ) and total matter density (Ω_M), most of which is dark, from [38].

– Mechanisms to suppress flavor changing neutral currents [39, 40], proton decay [17, 41], and electric dipole moments [40, 42]. These are automatically absent or strongly suppressed in the SM, but are present at some level in almost all extensions. There are experimental opportunities to greatly improve limits or observe rare μ, τ, B, and K decays (or $\mu - e$ conversion); neutron, electron, or atomic EDMs; and proton decay. These are extremely important complements

to the future collider program.

3.2 TeV Physics from the Top Down

Speculations concerning new physics at the TeV scale are often motivated by attempts to solve the problems of the standard model. For example, supersymmetry, dynamical symmetry breaking, Little Higgs models, and large extra dimensions (LED) are all motivated at least in part by the fine tuning associated with the Higgs mass in the SM. It is entirely possible, however, that there may be new TeV scale physics in addition to (or instead of) the above that does not directly solve any SM problem, but which simply emerges as a remnant of the underlying physics at a much higher mass scale [43]. For example, concrete semi-realistic superstring constructions often lead to such new physics as: (a) Additional Z' gauge bosons or other new interactions. These are especially common [44], not only in string constructions but also in dynamical symmetry breaking [20], Little Higgs [19], and LED [21]. New Z's may have implications for a highly non-standard Higgs sector, baryogenesis, cold dark matter, and FCNC. (b) New exotic particles are very common. These may include additional Higgs singlets and Higgs doublet pairs (all of which can mix, and which may yield new sources of CP violation and FCNC), quarks and leptons with non-canonical weak interactions (e.g., heavy charge $-1/3$ quarks $D_{L,R}$, both of which are $SU(2)$ singlets [45]), or even fractional electric charges such as $\pm 1/2$ (the latter usually couple also to a hidden sector and *may* be confined). (c) Quasi-hidden sector gauge groups. If strongly coupled these may be associated with supersymmetry breaking by gaugino condensation. However, they are not always strongly coupled. There are usually a few particles that couple to both the ordinary and hidden sectors (hence the term quasi). Extra $U(1)'s$ also often couple to both sectors.

Of course, such things may simply be flaws in the constructions studied, but they may also be hinting that there really is TeV physics beyond the MSSM. In particular, superstring model builders should not necessarily assume that the ultimate goal is to obtain the MSSM.

4   Conclusions

The Standard Model is spectacularly successful, and successfully describes nature down to a distance scale a thousandth the size of the atomic nucleus. However, the SM has many parameters, tunings, and unexplained features, indicating that there must be underlying new physics that manifests itself on shorter distance scales. There are many theoretical ideas, including superstrings, Grand Unification [17] (including canonical GUTs in 4 dimensions and modified versions which only fully manifest themselves in higher dimensions, e.g., within a string theory), and supersymmetry. Even Planck or GUT-scale physics may leave telltale signatures at the TeV scale, such as Z's, extended Higgs sectors, and exotic particles. Other theoretical ideas include large extra dimensions (and deconstruction), dynamical symmetry breaking, compositeness, and Little Higgs models.

The TeV scale may well be extremely complicated. Fortunately, we can look forward to a variety of experimental probes. These include hadron colliders (the Tevatron and LHC) and linear colliders (the International Linear Collider and CLIC) to explore the energy frontier. In addition, there will be a (very important) complementary program of lower energy probes, including detailed explorations of off-diagonal CP violation, rare decays, and FCNC at B factories and in K, μ, and τ decays; more precise measurements of n, e, and atomic EDM; precision experiments; neutrino physics; p decay; and new observations in cosmology/astrophysics, including ground and space based studies of dark matter and dark energy.

There are tremendous opportunities in particle physics. There are theoretical ideas and experimental facilities that could possibly - if we are extremely lucky - allow us to develop and test a new standard theory valid all the way to the Planck scale.

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